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The changing water cycle: hydroclimatic extremes in the British Isles

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This focus article is concerned with long-term changes in hydroclimatic extremes across the British Isles. The combination of short records, poor data quality, non-stationarity and other methodological constraints is a major obstacle to the attribution of change. Given the interaction of drivers, notably hydroclimate and land use, linking cause and effect can be difficult, especially where records are short. This focus article emphasises the particular value of long hydrological records in seeking to understand the scale of change currently affecting British and Irish river basins. Homogeneous records of precipitation and river flow are used to explore long-term changes and to establish linkage with large-scale atmospheric drivers. Using very long records allows subtle, underlying trends to be detected within noisy records; since most records of river flow are only a few decades long, very long precipitation records are used to provide a context and evidence of century-scale monotonic trends. Analysis of flow extremes in the British Isles shows a clear linkage with indices of large-scale atmospheric circulation; relatively simply indices of weather type and atmospheric circulation provide a good level of explanation. At the longest timescales, there has been important variation in precipitation: a monotonic increase in winter, not seen in summer where inter-decadal variability is the dominant pattern. With one exception, significant trends in summer are negative, including in the uplands; this unexpected result deserves further consideration across the British Isles.

INTRODUCTION

Quantitative analysis of hydrological systems is long established but it still remains difficult to understand why change is happening and to predict future system behaviour. The combination of short records, poor data quality, non-stationarity and other methodological constraints is a major obstacle to the attribution of change[1]. A particular problem is that river basins are sensitive to multiple drivers, climate and land use change being the most important. These two drivers are not independent, of course: for example, as the climate warms, new crops may be introduced, with new impacts on the local environment; this might in turn increase rates of water abstraction, reducing discharge rates, especially noticeable at low flow. Given this interaction of drivers, linking cause and effect can be difficult, especially where records are short. This focus article emphasises the particular value of long hydrological records in seeking to understand the scale of change currently affecting

UK river basins. Homogeneous records of precipitation and river flow are used to explore long-term changes in the hydroclimatology of UK river basins, looking at both (annual and seasonal) mean values and extremes.

The evidence for human influence on the global climate system is unequivocal. The latest Intergovernmental Panel on Climate Change Report[2] concluded that it is *extremely likely* that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together. An increase in global temperature will be accompanied by an increase in global precipitation: averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901 (*medium confidence* before *and high confidence* after 1951). Relative to 1850–1900, global surface temperature change at the end of the 21st century (2081–2100) is projected to *likely* exceed 1.5°C but resultant changes in precipitation in a warming world will not be uniform. In many mid-latitude wet regions, mean precipitation will *likely* increase with very high greenhouse gas emissions. Extreme precipitation events over most mid-latitude land masses will *very likely* become more intense and more frequent as global mean surface temperature increases[3].

The considerable degree of uncertainty about the regional-scale impact of climate change is particularly problematic for the UK, given its mid-latitude location on the eastern edge of the Atlantic Ocean and the western edge of the Eurasian continent. The UK is strongly influenced by the North Atlantic Oscillation (NAO), the most important mode of climatic variability in the northern hemisphere. It controls the strength of westerly winds between the 'Azores high' and the 'Icelandic low' that bring a succession of weather systems to Western Europe[4]. European climate in general exhibits a dipolar signal due to changes in the NAO: northern and southern Europe experience opposite effects, with northern Europe having more frequent and intense winter rainfall from westerly circulation systems in comparison to southern Europe[5,6]. The UK's location means that it significantly affected by the dipole signal, with seasonal and spatial variations in precipitation as a result.

Global Climate Model (GCM) output needs to be downscaled to reflect regional climatic conditions but the resolution may still be insufficient given the scale of topographic variation experienced locally across the UK[7]. Given the lack of reliable information given by GCMs on the potential hydrological impact of climate change at small spatial and temporal scales, dynamical downscaling has been used to provide a more appropriate scale of climatic output than GCMs for hydrological impact studies[8]. However, most climate scenarios do not incorporate potential changes in the characteristics of daily rainfall or its year to year variability[9] and it seems not enough to simply adjust means ("bias correction")[8]. Better knowledge of hydroclimatic variability in the past should help improve hydrological projections in the future, via improved verification of downscaling output.

As well as the potential to achieve better forecast via modelling, better understanding of the atmospheric circulation over the North Atlantic is improving seasonal forecasting of precipitation and river flow. Skilful seasonal predictions of UK river flows are now a viable proposition and have recently become available for the UK on a year-round, national scale, These consist of predictions based on flow persistence, historical flow analogues and hydrological modelling[10]. With winter rainfall projected to increase in future, increasing the risk of extreme events such as those of winter 2013/14[11] and winter 2015/16, the ability to provide early warning of flood risk will be important in itself, as well as more generally for adaptation to climate change.

Here, we focus not on model output but on historical changes in river flow and the climatic drivers responsible: precipitation and actual evaporation. Stations are selected from across the British Isles on the basis of length of record and spatial distribution. We examine a number of aspects of these variables, flow extremes as well as annual and seasonal means since some show changes at the inter-decadal time scale but others do not; such knowledge is vital if downscaling model output is to be made more appropriate for hydrological projection. Given high local variability between catchments, the value of long records is particularly important, as it is difficult to generalise from short records. Since it can be hard to distinguish subtle signals from noisy records[12,13], water resource planners must be aware that adaptation responses may well be needed before statistically significant change can be identified. This is in turn may require new approaches to the detection of change in hydrological systems[14].

QUANTIFYING HYDROCLIMATIC EXTREMES

Traditionally, hydroclimatic extremes have been quantified using extreme frequency analysis: this allowed the estimation of a particular value (e.g. peak flood discharge, Q) which is likely to be equalled or exceeded once in a specified period, T years. The concept of the return period states that the T-year event, Q_T, is the average chance of exceedance every T years over a long period[15]. However, even a single-variable analysis requires choice of precisely which variable to consider (e.g. rainfall totals over a number of hours) and the decision whether to use the annual maximum or a partial duration (peak-over-threshold) approach. Of course, extreme precipitation totals may not exactly equate to storminess (e.g. the frequency and intensity of cyclones[16]). For extreme droughts, there are again more choices to be made[17]: whether just to rely on measures of river flow deficiency (e.g. Q_{95}), a measure of precipitation deficit (e.g. cumulative deviation from average), or another measure such as groundwater table level or spring flow[18]. Traditional risk assessment relying on a single variable may not accurately represent extremes and lead to significant underestimation of risk; for this reason, multivariate copulas (a function linking marginal variables into a multivariate distribution) have been increasingly used for assessing the relationship between climate variables and extremes[19]. These can comprise simple composites like the Davis summer weather index[20] or more complex functions derived from principal components analysis. Reassessment of flood risk can augment single-site analysis with pooled analysis of multi-site data and historical records of flood peaks[21]. Increasingly too, rather than using single-site observations, historical analyses are based on reanalysis data sets for gridded areas[16,22-24] with forward projections based on climate model ensembles[25]. In addition to univariate and multivariate data-based approaches, there are a range of proxy data that can be used e.g. tree rings, lake varves, historical documents; such evidence can extend the timeframe of analysis well beyond the period of instrumental record[26].

Our emphasis here is on very long instrumental records from across the British Isles. We aim to cover not just river flow records, most of which are only a few decades long, but also other hydroclimatic records, notably precipitation, a number of which are over a century long. Whilst this raises issues about the homogeneity of records[27], especially where measurement methods have changed over the years or where it is necessary to blend records from nearby sites[28], enough checking has been done to give confidence in the records and subsequent analysis[29]. The analyses presented here are mainly based on daily data: river flow data may well have been derived from 15-minute observations but daily averages are sufficient to complement precipitation and other hydroclimatic data which tend to be daily totals or averages. Only in recent decades have sub-daily precipitation records become available via data loggers and the availability of such data remains patchy in space and time[30]. We examine a number of very long daily rainfall records for selected meteorological stations. This is important because, when viewed over shorter time periods, such records can show a variety of trends, increasing or decreasing, because of natural, decade-scale oscillations[31]. Using very long records allows us to detect subtle, underlying trends within noisy records[32]. Where gaps were present, data from nearby stations (usually within a few kilometres) were inserted. Usually, no attempt has been made to adjust infill data given the proximity of stations but this may be necessary for upland gauges where precipitation gradients can be very steep. Of course, infilling becomes much more problematic with very early records, but fortunately a few long, high-quality daily records are available (Oxford, Armagh, Durham) supplemented by monthly totals for some other sites (Edinburgh, Kew). With very long records, there are always concerns about changing instrument type or location. Fortunately, at a few sites (e.g. Radcliffe Observatory, Oxford[29]), considerable effort has been expended to ensure that, when new instruments were set up or old ones moved to a different position, there was cross-comparison between old and new records, with adjustments made accordingly.

The problem of testing hydroclimatic data for trend in time has received considerable attention. Some of the characteristics that complicate the analysis of such time series are non-normal distributions, seasonality, flow relatedness, missing values, and most relevant here, serial correlation[33]. Because parametric tests assume that the data are normally distributed, non-parametric tests such as Spearman's Rank (SR) or the Mann-Kendall (MK) test are often used instead; these distribution-free tests have the advantage that their power and significance are not affected by the actual distribution of the data[34]. Long-term persistence is often identified in hydroclimatological time series, preventing the individual data from being treated as statistically random. One of the assumptions of linear regression analysis is that the residual error terms are independent from one another i.e. they are uncorrelated. Although there are many ways this assumption might be violated, the most common occurs with time series data in the form of *serial correlation*: in the context of a time series, the error in a period influences the error in a subsequent period – the next period or beyond. To overcome the issue of serial correlation, tests such as the Durbin-Watson (DW) statistic are used to detect the presence of autocorrelation (a relationship between values separated from each other by a given time lag) in the residuals (prediction errors) from a linear regression analysis; the distribution of this test statistic does not depend on the estimated regression coefficients or the variance of the errors. There have been many reviews of how properly to analyse trends in hydrological data[33-39]. If the hydrological time series is not subject to significant serial correlation, then tests such as SR and MK can be executed without need of correction for the effect of serial dependence on the tests[40]. Recently, there has been concern that the use of the p-value, or statistical significance, does not measure the size of an effect or the importance of a result[41]. Here, we use the DW statistic to test for serial correlation and then apply both MK and SR to test for a significant trend; the latter is helpful since it indicates the strength of the trend as well as its direction. Note that an apparently low value of a correlation coefficient may nevertheless be statistically significant for a long time series. It is worthwhile considering both the power of the result as well as its significance therefore. Given that the signal-to-noise ratio is often very small in natural systems, making subtle trends hard to detect[12, 32], but given also concerns about measures of statistical significance[41], it is important, where possible, not to rely on single results but to provide additional evidence. This can be difficult given the rarity of very long time series but, where we can, we try here to provide results from more than one location across the British Isles.

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Because hydrological extremes are expected to become more common in a changing climate, hydroclimatological projections can help improve planning of water resources and increase human preparedness for hydrological extremes, including floods and droughts[42] and indeed there has been a proliferation of studies seeking to attribute changes in observed hydrological series (whether gradual trend, abrupt change or more complex forms) at the catchment scale in recent years[3,4,7, 10, 43-50]. Reliable seasonal predictions of precipitation and river flow anomalies can be derived over large regions from indices of large-scale climatic circulation or from sea-surface temperatures, although caution is again required given potential issues of serial correlation, as already discussed. Rather than use statistical analysis, an alternative approach is to use simulation models to identify changes in runoff as a response to changes in driving hydroclimatic variables[51]. The method of multiple working hypotheses involves development, prior to analysis, of several hypotheses that might explain the phenomenon being observed, while explicitly recognising the possibility that more than one hypothesis may be simultaneously valid[47]. Some authors have criticised a lack of rigour in attributing observed climate change signals to potential drivers[50]. However, this “soft” approach may indicate an exploratory rather than a confirmatory approach, often typical of the initial stages of analysis[52] in which case further work is then needed to securely detect change and correctly attribute the causes.

HISTORICAL CHANGES IN CLIMATIC DRIVERS

The data sets presented here are deliberately selective rather than providing comprehensive coverage across the British Isles (Figure 1). In any case, our focus on very long records necessarily limited our choice. Our purpose was to make the time scale as long as possible. A consistent approach using a larger number of precipitation records is certainly possible[49] but, as noted below, river flow records of more than a few decades are rare.

Precipitation

In this section, our objective is to provide a context for long-term changes in river flow by looking at climatic drivers, heavy falls of rain in particular. The intensification of precipitation extremes with climate change is of key importance to society as a result of the large impact through flooding[3]. The analysis is not exhaustive, more a snapshot using some very long records. Ideally, more than one trend testing method should be used[36, 53]. Note that most of the regression and correlation results reported here are for Pearson linear regression and product-moment correlation (r). However, for trends over time, to avoid any assumption about data distribution,, the SR correlation coefficient (r_s) is quoted instead (Table 1), although in practice this makes little difference to the reported correlation coefficients or their statistical significance. No significant value of r_s is quoted unless the MK test result was also significant and no test for correlation was carried out unless there was no significant serial correlation.

We start with data from the Radcliffe Observatory at Oxford (monthly record from 1767, daily data from 1827[29]) and then refer to other sites as necessary. Figure 2 shows annual rainfall totals from 1767, plus a decadal running mean. Despite a good deal of inter-decadal variability, there has been a general upward trend ever since the extreme drought of the 1780s. The overall linear trend is highly significant despite the low correlation coefficient (r_s = 0.189, p = 0.0038, n = 248); the time series starting in 1780 has an even stronger trend (r_s = 0.27, p < 0.0001, n = 235). The long-term linear trend in mean air temperature (data from 1815) is also very strong, as might be expected (r_s = 0.402, p <0.0001, n = 200) and, taken together, these two results might suggest a possible long-term temperature-precipitation linkage. Note, however, that the mean air temperature series from 1815 exhibits significant serial correlation (DW = 1.514, p=0.0002), so this makes it harder to argue for a significant, long-term correlation between temperature and rainfall.

In terms of seasons, there are significant upward trends in precipitation in winter (r_s = 0.308, p<0.0001) and spring (r_s = 0.212, p=0.0012) but not in summer or autumn. Figure 3 shows decadal running means for winter and summer, together with the winter to summer ratio expressed as a percentage. Both seasons show a good deal of inter-decadal variability with the upward trend in winter already noted. There was a tendency for summers to become drier during the 20th Century but this trend has reversed in recent years. For summers, inter-decadal variability tends to dominate, whereas in winter significant monotonic trends have tended to emerge, notwithstanding the decade-scale patterns of variation. Note that summers were particularly dry in the first part of the 19th Century. Thus, the increasing contrast between winter and summer rainfall, a pattern which is predicted into the future as an outcome of downscaling, is mainly the result of wetter winters. The winter to summer ratio was at its largest in the 1990s but has reversed in the last decade, reminding us that a future hydroclimate may be no less varied than in the past. Note that the long-term trends from 1767 for winter and spring total precipitation remain significant for the period 1827 to 2015 and for winter alone for the period 1857 to 2015. However, none of the correlations for shorter periods (i.e. later start dates) are significant; trend identification is therefore very sensitive to the start date of the time series.

Figure 4 shows the annual number of rain days (daily totals of at least 0.25 mm) at Oxford since 1827. Overall, there has apparently been a significant upward trend (r_s = 0.327, p <0.0001, n = 188), but the evidence is less convincing than for total rainfall. We are not confident that rainfall totals were recorded every day from 1827; even including days when precipitation is mentioned but not recorded, the total number of rain days appears low through to 1850 (when ground-level measurements began[29]), so there must be some ongoing doubt about the early observations. There is also the possibility of under-catch of snowfall early in the record and corrections to the record may not have taken this fully into account[29]. There is no significant trend in the annual total of rain days since 1850, underlining doubts about the reliability of the early record. There has been an apparent increase in the number of rain days in winter, spring and autumn since 1827, but from 1850 none of the seasonal trends are significant. There is no reason to doubt the drop in the number of rain days since the 1950s, and there has been a concomitant increase in the mean rain per rain day in recent decades, from 3.7 mm/day in 1950 to 4.6 mm/day in 2014. Discounting the pre-1850 records, mean rain per rain day has tended to increase at Oxford, significantly over the last 100 years, as at other stations in south-east England[54]; the annual trend from 1850 is weak but statistically significant ($r_s = 0.162$, $p = 0.038$). Note that a significant upward trend is evident for the number of daily totals of 1 mm in winter ($r_s = 0.274$, $p = 0.0006$), spring ($r_s = 0.24$, $p = 0.0028$) and for the year as a whole ($r_s = 0.274$, $p = 0.0006$) and for number of daily totals exceeding 5 mm in winter ($r_s = 0.215$, $p = 0.006$) but not for numbers of daily totals of 10 mm or more.

In terms of large daily totals (data not presented), there has been no significant change over the study period at Oxford, for seasonal or annual data. Since the 1850s, the numbers of daily totals of at least 15 mm has averaged six per year, ranging from only one in 1902 to 17 in the record-breaking year of 2012. The same lack of long-term trend is seen for the T10 index[55] which at Oxford is a daily total of 22 mm. There is a no significant trend in the annual daily maximum totals since 1827 ($r_s = 0.09$, $p = 0.21$). To summarise the Oxford precipitation data, there is some evidence of monotonic linear trends in winter, spring and annual totals, the frequency of precipitation events (as indicated by the number of rain days) and in the number of small daily totals (up to 5 mm). There is no evidence of any significant trend in the magnitude or frequency of heavy falls of rain. Whilst there is good reason to expect that the long-term tendency for drier summers, as projected by downscaling, is likely to continue, the increase in summer rainfall at Oxford in recent years seems to accord with the 2009 UK Climate Projections, which were too uncertain to say whether seasonal totals might increase or decrease[56]. However, there is some expectation of more intense events at sub-daily timescales[3], showing the need for further analysis of sub-daily rainfall data.

Table 1 shows evidence of long-term trends in seasonal rainfall totals across the British Isles following analysis of 35 of the longest records available. Ten records show a significant upward trend in annual rainfall total, usually as a result of significant increases in winter, spring or autumn. Negative trends in annual totals at three sites result from the dominant influence of drier summers, over-riding any changes in other seasons. This is particularly notable at two very wet upland sites, Poaka Beck (Lake District) and Princetown (Dartmoor), where the impact of the NAO in summer appears particularly influential (see below). Significant trends in summer are downward, except at Hereford. Given the amount of inter-annual and inter-decadal variability, the relatively small number of significant trends is not surprising: subtle signals may be hard to detect in very noisy records[12,13]. Figure 5 shows summer rainfall at Poaka Beck in the western Lake District hills.

Temperature, evaporation and drought

The long-term trend in annual mean air temperature (MAT) at Oxford is highly significant (although there is significant serial correlation, as already noted). Potential evaporation (PET) and actual evaporation (AET) have been modelled at Oxford[57] from 1815 to 1997. PET was estimated using the Thornthwaite method and so, being strongly dependent on MAT, PET shows a significant upward trend over time (r_s = 0.251, p = 0.001; unlike the temperature record, there is no significant serial correlation). However, there is no significant trend in AET. Annual runoff (Q) is calculated as precipitation (P) minus AET; there is no long-term trend in Q either.

Whilst meteorological drought obviously depends in part on air temperature, deficit in precipitation receipt is the main control, especially for longer durations. Here, we use running totals as an indicator of drought severity. Figure 6a shows 24-month running totals at Oxford; this is a good indicator of severe droughts where two dry summers are separated by a dry winter, as in 1975-76[58]. A 24-month period will be more relevant to surface water resources where reservoir storage is particularly dependent on winter recharge, whereas summer drawdown is related to high air temperatures as well as lack of rainfall. The 60-month running totals (Figure 6b) show very extended droughts, most relevant to major aquifers like the Chalk of south-east England; water resources in the Chalk can withstand a couple of dry years but will become greatly stressed by a very protracted dry period. Whilst the 1987-1992 drought, as indicated by the Oxford rainfall record, was not the most severe on record in absolute terms[59], in relation to the local mean, the 1987-92 rainfall deficit was in fact comparable to the late 18th and late 19th century droughts – and at a time of much greater water use in the region, of course. Thus, even with increasing precipitation totals, very severe droughts can still occur and in relation to the local 30-year mean, severe droughts remain as likely to occur as in the past two centuries. At Poaka Beck in the wet uplands, there is evidence of falling 24-month and 60-month totals, reflecting the overall fall in summer precipitation totals as already noted above (Figure 7). This could mean that water shortages during long droughts will become more severe at such upland sites, particularly problematic if winters are drier than normal and reservoirs are not full by the start of the following summer. However, the general pattern in the uplands has been for wetter winters and drier summers[60], in other there has been increased hydrological variability recently, very dry winters are uncommon, and full reservoir recharge is very likely in most winters.

Climatic drivers

A variety of indices may be used to characterise the influence of atmospheric circulation on climate. Given strong collinearity between these drivers[49], here we mainly use just three indices to indicate the primary controls: the Lamb Weather Types (LWT) cyclonic (C) and westerly (W), and the North Atlantic Oscillation index (NAOI). We use the Lamb counting method to produce totals of C and W weather types each month[49]. Table 2 shows correlations by season and year at Oxford: data from 1871 when the LWT series begins. There are extremely strong positive correlations between seasonal and annual rainfall totals and the C count but none with W or NAOI. Another study[49] has confirmed a very strong positive correlation between annual rainfall totals at Oxford and atmospheric vorticity and a very strong negative correlation with anticyclonic conditions (but note that results presented here differ slightly because of the different length of records analysed). Cyclonic conditions are an important control of number of rain days, number of days with at least 15 mm, and 10-day accumulation totals in winter. Mean air temperature is generally well correlated with all three climatic indices; so too AET with C in summer, autumn and for the year as a whole, and with W and NAOI in winter and spring. Q (P – AET) correlates strongly with C for all seasons and year but not with the other two climatic drivers except W in winter. At the upland Poaka Beck, whilst the frequency of C days remains very influential, so too is the frequency of W days and the strength of the NAO (except in summer). Positive correlations with NAOI at Poaka Beck indicate the importance of "double orographic enhancement" in the British uplands[7]: when the NAOI is highly positive, any increase in rainfall is amplified with altitude (Table 3).

The frequency of cyclonic conditions is highly important at both Armagh and Durham, both lowland sites, compared to the other indices, for total rainfall and number of rain days. C remains important at Durham for number of days with at least 15 mm and the 10-day accumulated total count, but less so at Armagh. Note that correlations with NAOI are positive at Armagh but negative at Durham, an important longitudinal contrast across the British Isles. Armagh is relatively close to the main depression track in the North Atlantic whereas Durham's response is more reflective of eastern England, no doubt influenced in large part by being in the rain shadow of the Pennines but also subject to a somewhat more continental climate[7].

In relation to drought, we used 2-year and 5-year totals and correlated these with average values for the climatic indices for the same period. Given the start of the LWT series in 1871, our results run from 1872 for 2-year totals (n=144) and from 1875 for the 5-year totals (n=141). In both cases, rainfall totals are very strongly correlated with C ($p < 0.001$). There are other significant correlations but no consistency except with C. This suggests that, as might be expected, a protracted prevalence of anticyclonic conditions is the main driver of major, extended droughts across the British Isles. An association has been noted between La Niña episodes and winter rainfall deficits in some major multi-annual drought episodes in the English Lowlands[52]. We could find no link to the El Nino Southern Oscillation (ENSO) except for 60-month droughts at Armagh. There is a significant downward trend in summer rainfall at Armagh since 1850 (p=0.017) and weak but insignificant association of summer rainfall with the summer value of the NAOI (p=0.16) [not to be confused with sNAO[61]], suggesting that a negative trend in NAOI is increasing the likelihood of droughts in western locations generally. Other sites close to the east coast of the island of Ireland show a significant correlation between summer rainfall and summer NAOI[62]; further work is needed to explain how the changes in the summer NAO are resulting in lower rainfall in this region.

The important conclusion from this section is that there are simple indices of atmospheric drivers that can be successfully correlated with hydroclimatic response. This suggests that a similar approach could be adopted with river flow, offering the possibility of projection as well as historical interpretation.

HISTORICAL CHANGES IN RIVER FLOW

Trends

In general, records of river flow are much shorter than climatic records. With the exception of the Thames at Kingston (from 1883), only a few UK records start before 1950. Because of significant inter-decadal variability, short records may indicate trends which do not reflect longer-term changes[32]. It is possible to reconstruct past river flow records from precipitation data[63], but this is hardly an independent test – if precipitation shows a trend, likely so too will river flow[14]. However, such reconstructions can be useful to compare actual and "naturalised" flows.

Figure 8 shows decadal running means for River Thames at Kingston and annual runoff[57] calculated using Oxford weather records (Q: see above). There are two reasons why the Oxford record might consistently underestimate the actual Thames river flow by about 60 mm: either AET is overestimated or the Oxford rainfall total is lower than the catchment average. There is nevertheless a highly significant correlation between the two records ($r = 0.663$, $n = 104$, $p << 0.0001$). Although rainfall total has a significant upward trend, predicted river flow (Q) does not. Nor does actual river flow from 1883; indeed, there is a downward trend throughout the 20th Century. Numbers of days above the Q10 and Q5 thresholds show no long-term trend either.

A detailed analysis of the Thames river flow record detected no trend in fluvial flood magnitude, partly reflecting a decline in snowmelt contributions to major floods; annual maximum lock levels showed a significant decline, reflecting a highly sustained programme of river management, for water abstraction in particular[64]. Figure 9 shows annual river flow for the Thames at Kingston (Figure 9a) plus three measures of extreme flow. Unlike rainfall, the general tendency for annual mean gauged daily flow is downwards ($r_s = -0.246$, $p=0.014$), at least from the 1910s onwards (Figure 9a). There are no significant long-term trends in extreme high flow. Figure 9b shows number of days exceeding the T10 threshold; this index is the flow rate above which 10% of the total flow occurs and matches a similar index for daily rainfall[49]. The pattern is not dissimilar to the flow record except that the number of T10 events seems to have increased since the 1980s, perhaps as a result of wetter winters in the 1980s and 1990s. Note especially high numbers of T10 events in the very wet winter of 2000-1 and the record-breaking winter of 2013-14[65]; whilst unparalleled in the record, these recent high values are no proof of the impact of climate change. Figure 9c shows the number of days exceeding the Q5 index for 10-day flow totals; the Q5 index identifies the level above which river flow occurs less than 5% of the time. Again this looks very similar to the total flow record shown in Figure 9a. Figure 9d shows the number of days falling below the Q95 flow threshold. Since the 1980s, there have been more days of low summer flow, a result of the dry summers in the 1990s. There has been some reversal (i.e. fewer low flow days) in recent years as a result of wetter summers. Taken together, these results indicate the influence of climatic variability on the Thames river flow regime rather than any clear long-term trends. Note that there will be greater than usual abstraction during dry summers; this will help produce more low-flow days in the gauged flow record[43, 64]. Figure 10 provides the <u>naturalised</u> flow record for the Thames at Kingston, mirroring the results in Figure 9. Note that the naturalised flow record does not show a significant downward trend from the 1910s; moreover, there is a significant upward trend for the whole naturalised flow record from 1883 ($r_s = 0.208$, $p = 0.017$), reflecting the upward trend in rainfall. Thus, the effect of increasing abstraction through the 20th century on the actual flow record is clear. This is underlined by the numbers of days below the Q95 threshold: there are relatively few of these in the naturalised flow record from the 1970s onwards (Figure 10d), quite different to the gauged flow record, as already noted (Figure 9d).

For catchments in the north and west of the British Isles, those especially with upland headwaters, there were significant increases in flow from the 1960s to the early 2000s but such trends are not necessarily seen if analyses are extended back to the 1930s[66, 67]; yet again, trend detection is very sensitive to length of record[14]. There is a significant upward trends for the Tay from 1953 (NRFA 15006, $r_s = 0.504$, $p = 0.0002$) but not for the Tees (NRFA 25001) or the Exe (NRFA 45001).

Climatic drivers of river flow

The analysis here follows other similar studies, relating indices of river flow to atmospheric drivers such as NAOI and Lamb Weather Types[46, 48]. Across the British Isles, there are significant *positive* relationships between NAOI and total winter rainfall in the northern and western uplands but these are almost completely absent further south and east in the lowlands[6]. NAO impact on winter rainfall totals translates directly to river flow, with highly significant correlations in both large and small basins. As with rainfall, the only negative relationship between winter flow and NAOI is in north east England (River Coquet: 22001)[7]. There are fewer significant relationships with NAOI in spring and autumn, only found in upland locations or at NW coastal locations. There are highly significant correlations between NAOI and river flow for the Tees ($r = 0.49$), Exe ($r = 0.359$) and Tay ($r = 0.723$) in winter but not for the Thames.

There are significant *negative* relationships between summer NAOI and summer river flow for many sites in lowland, southern and eastern England. This opposite effect in summer, in terms of both sign and location, is not unexpected: summer brings a weaker NAO, and the Azores anticyclone tends to cover much of the North Atlantic[7]. Figure 11 shows summer rainfall at Whitby since 1962 and summer river flow at Derwent Buttercrambe (NRFA 27041) since 1974. Despite drier summers in the 1990s, the general trend has been an increase in totals over time, helped by a run of wetter summers in the 2000s. There is a significant trend for rainfall ($r_s = 0.284$, $p = 0.05$) but not for river flow. Correlations of summer rainfall and river flow with the summer NAOI are highly significant ($r = -0.46$ and -0.52 respectively, $p = 0.0006$ in both cases). In summer, only the correlations between the summer value of NAOI and river flow for the Exe ($r = -0.38$) and Tees ($r = -0.37$) are significant, although the trend for the Thames is only nearly so ($r = -0.16$, $p = 0.064$); in all these cases the summer correlations with summer NAOI are negative, as expected. There is some disagreement as to whether the large-scale climatic circulation correlations with river flow are stronger or weaker in summer compared to those for precipitation[7, 44]. Comparing Oxford rainfall and the Thames river flow for the period 1883-1997, neither shows a significant correlation with NAO but there are strong correlations with C. These include lagged correlations with C in the previous winter and spring, something that has been noted in other analyses too[68]. Whilst summer rainfall is bound to be locally variable in time and space, river flow provides a more integrated response to climatic drivers, including antecedent conditions. Where particular circulation types persist, for example C and W in 2012, strong correlations for river flow might relate as much to prior as to current conditions. A comprehensive analysis for river basins across the British Isles would seem merited, to include possible lagged effects. A regional approach to water balance would also be useful, noting that evaporation data used here are limited to one site, Oxford. The abiding issue remains the relative shortness of river flow records so it is important to look at the statistical significance of the correlations rather than the magnitude of the correlation coefficient itself[7]. Further work might be fruitful using sNAO instead of summer NAOI as an indicator of summer climate[61] in order to better explain changing patterns of summer rainfall across the British Isles. The same might be said of indices of low-frequency climate forcing such as the Atlantic Multidecadal Oscillation (AMO)[69]; such indices could improve levels of explanation, especially in summer where inter-decadal variability tends to be the dominant pattern.

Like extended rainfall totals at Oxford, 24- and 60-month river flow totals for the Thames are highly correlated with W and especially C, but not with NAOI. For 24-month flow totals, the correlation with C is 0.65 ($p << 0.0001$) and with W is -0.3 ($p = 0.0005$). For 60-month flow totals, the correlation with C is 0.54 ($p << 0.0001$) and with W is -0.32 ($p = 0.0003$). These results confirm the importance of cyclone frequency in driving seasonal precipitation totals[48, 49, 65]. The negative correlation with W shows that, when there is a strong westerly air flow over the British Isles as a whole, there is a lack of rain-bearing cyclonic conditions in the south east. Thus, extended low-flow periods relate strongly to a prevalence of anticyclonic conditions and a relative absence cyclonic air flow over the Thames basin. For the Exe, the only (very) significant correlations for 24- and 60-month river flow are with C ($r = 0.7$ and 0.68 respectively). For the Tay, the correlation of 24-month flow totals with NAOI is just significant ($r = 0.27$, $p = 0.04$) but there is a very strong positive correlation with W ($r = 0.65$, $p << 0.0001$). For 60-month river flow on the Tay, the only (highly significant, positive) correlation is again with W ($r = 0.68$, $p << 0.0001$). For the Tees, the only (highly significant) correlations are with C (0.61, 0.55). Thus, lack of cyclonic conditions will tend to cause low flows in the east and south whereas lack of westerlies leads to low river flow in the north and west.

Looking at flow frequency data and the number of days above or below a particular threshold, much the same results are seen as for mean river flow. Taking annual totals for the River Thames since 1883, the number of high-flow days is significantly correlated with C: Q5 has a correlation of 0.56 and for Q10 the correlation is 0.44 ($p <<0.0001$ in both cases). There is also a highly significant correlation with the number of peaks over the T10 threshold (POT; $r = 0.42$). The number of days where flow falls below the Q95 value is negatively correlated with C ($r = -0.38$) and positively with W ($r = +0.31$). For the Exe, the only (highly significant, $p < 0.001$) correlations are with C: Q5 ($r = 0.5$), Q10 ($r = 0.53$), POT ($r = 0.53$) and Q95 ($r = -0.41$). For the Tees, again the only (highly significant) correlations are with C: Q5 and Q10 ($r = +0.65$ for both), POT ($r = 0.43$); there is no result for Q95 because the baseflow regime for the Tees has changed fundamentally since the construction of Cow Green reservoir in the 1970s. For the Tay, the most significant correlations (Q5, Q10, POT) are with W ($P<0.001$) but there are also strong correlations with NAOI ($p<0.01$). The importance of westerly air flow across the northern uplands is clear, providing high levels of river flow via orographic enhancement of rainfall[7]. For the number of days below Q95, there is a significant negative correlation with C ($r = -0.297$, $p<0.05$), indicating the importance of anticyclonic conditions for low flows in upland, northern catchments, and *vice versa*.

Table 4 shows an updated analysis[49] of LWTs for peaks in river flow that exceed the T10 threshold[55] together with LWTs for one and two days before the peak for the River Tay. As expected from results reported in the previous paragraph, C is dominant on the day of peak flow for the Exe, Thames and Tees, but W is dominant on the Tay. For the Tay, S and W are more important the day before when the flood hydrograph is likely to have been generated; similar results were obtained for the Tees and Exe[49]. For the largest basin included, the Thames in southeast England, C dominates for day-1 as well, again indicating the importance of cyclonic conditions for widespread rainfall across the lowland east and south-east of the country.

Finally, it worth making the point that non-climatic drivers might well be more influential than climate and there is some evidence of this in the Thames flow record. The influence of abstraction on low flows has already been mentioned. Of course, the study period for the Thames basin has been one of significant urbanisation; comparing Figures 9 and 10, there is some suggestion of higher peak flows in the gauged flow record compared to the naturalised flow estimates, for both individual flood peaks (days above the T10 threshold) and for 10-day totals above the Q5 threshold. Urbanisation apart, arguably the most major change in land use since the 1880s was the ploughing of grassland in 1940[70] at the start of World War II, but no abrupt change in runoff is detectable in the Thames flow record. Thus, even spatially widespread changes in catchment conditions may not produce a significant response in terms of flow regime at the catchment outlet. Of course, changes in land use might complement or oppose the effect of climatic change; in the future, multivariate analyses involving both hydroclimatic and land use and land management data are needed to interpret long-term hydrological change therefore.

Conclusions

1. Given significant inter-decadal variability, short records may indicate trends which do not reflect longer-term changes. This is especially a problem for analysis of river flow records which are usually no more than a few decades long; in contrast, precipitation records of a century or more are relatively common. It is important to examine very long time series because, when viewed over shorter time periods, such records can show a variety of trends, increasing or decreasing, because of natural, long-term oscillations[31]. Using very long records allows us to detect subtle, underlying trends within noisy records[12, 32].

2. Analysis of flow extremes in the British Isles shows a clear linkage with indices of large-scale atmospheric circulation. In one sense this is hardly surprising but it useful nevertheless to know that the use of relatively simply indices can provide a good level of explanation. Improved forecasting of large-scale circulation can only be beneficial in relation to both precipitation and river flow, whether looking at mean values or the frequency and magnitude of extreme events[10]. This is much more problematic for the Atlantic Ocean than for the Pacific or Indian Oceans, but recently progress has been achieved in relation to the NAO, which can only be helpful in a British Isles context[44]. Of course, mean flow statistics may not reflect the occurrence of individual events so there is continuing need to improve forecasting of extreme river flow events, both in terms of hydroclimatology and meteorology.

3. At the longest timescales, there has been important variation in precipitation: a monotonic increase in winter, not seen in summer where inter-decadal variability is the dominant pattern. With one exception, significant trends in summer are negative, including in the uplands; this unexpected result deserves further consideration since it may have significant implications for river flow, low flows especially, and reservoir recharge. Whilst the tendency may be towards greater seasonality, there will nevertheless be summer flood-rich periods[71] in the future when extreme summer floods like those experienced in 2007 can be expected. Even if the mid-latitude response to global warming is a stronger Azores high in the eastern Atlantic in summer, extreme events can still happen in summer, as the historical record clearly shows. Given the results presented here, if extreme precipitation and river flow events are to be successfully anticipated, improved seasonal forecasting of large-scale atmospheric circulation in the northern Atlantic remains the holy grail.

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Table captions

1. Evidence of long-term trends in seasonal rainfall totals across the British Isles following analysis of 35 of the longest records available. All correlations are Spearman Rank. Stations omitted from Table 1 (no significant trends in any season): Appleby (1857), Bradford (1911), Burnhope (1931), Cambridge (1900), Douglas (1878), Durham (1850), Hampstead (1911), Malham Tarn (1870), Nairn (1931), Pembroke (1849), Southampton (1855) Spalding (1727), Stornaway (1874), Trevince (1889), Waterford (1941), Wick (1914). Ordinary font: significant at $p < 0.05$; italics: significant at $p < 0.01$; bold: significant at $p < 0.001$.
2. Significant correlations at Oxford by season and year for various precipitation indices. Data from 1871 when the LWT series begins.
3. Significant correlations at Poaka Beck by season and year for various precipitation indices. Data from 1874 when the rainfall series begins.
4. An updated analysis[43] of LWTs for peaks in river flow that exceed the T10 threshold.

Figure captions

1. Map of stations mentioned in the text
2. Annual rainfall totals at Oxford from 1767, plus a decadal running mean.
3. Decadal running means at Oxford for winter and summer, together with the winter to summer ratio expressed as a percentage.
4. Annual number of rain days (daily totals of at least 0.25 mm) at Oxford since 1827.
5. Summer rainfall totals at Poaka Beck, plus a decadal running mean.
6. Running totals of monthly rainfall at Oxford: (a) 24-month totals; (b) 60-month totals.
7. Running totals of monthly rainfall at Poaka Beck: (a) 24-month totals; (b) 60-month totals.
8. Decadal running means of river flow for the River Thames at Kingston (NRFA 39001) and annual runoff calculated using Oxford weather records[14].
9. Annual gauged flow statistics for the River Thames at Kingston: (a) mean gauged daily flow (mm); (b) number of days for which the mean daily flow exceeded the T10 threshold; (c) number of days for which the mean 10-day flow exceeded the Q5 threshold; (d) number of days for which the gauged flow was below the Q95 threshold. All data for water years beginning 1st October.
10. Annual naturalised flow statistics for the River Thames at Kingston: (a) mean naturalised daily flow (mm); (b) number of days for which the mean naturalised daily flow exceeded the T10 threshold; (c) number of days for which the mean naturalised 10-day flow exceeded the Q5 threshold; (d) number of days for which the naturalised flow was below the Q95 threshold. All data for water years beginning 1st October.
11. Summer rainfall at Whitby since 1961 and summer river flow at Derwent Buttercrambe (NRFA 27041) since 1974.

	start	winter	spring	summer	autumn	year
Oxford	1767	**0.307**	**0.212**			**0.189**
Edinburgh	1785		0.140			0.169
Armagh	1850			-0.158		
Abbotsinch	1857				*0.250*	
Fort William	1861		0.203		**0.353**	**0.334**
Batheaston	1871	0.218				
Braemar	1872			*-0.248*		
Poaka Beck	1874			*-0.249*		-0.189
Plymouth	1874	*0.289*	**0.336**		*0.243*	**0.385**
Ullscarf	1877					0.210
Dublin	1881	0.237				0.223
Hereford	1893	0.218	**0.335**	0.201	**0.304**	**0.496**
Eskdalemuir	1911		*0.313*		0.208	0.257
Trigon (Dorset)	1911			-0.257		-0.251
Upper Ryedale	1916	**0.381**	**0.331**		*0.278*	**0.516**
Princetown	1928			-0.271		-0.257
Coniston Holywath	1937	0.244	*0.324*	*-0.339*		
Valentia	1941					*0.358*

Table 1

	Total Rainfall	Rain days	Days>=15	10-day totals	MAT	AET	Q
Cwin	**0.719**	**0.635**	**0.324**	0.19			**0.721**
Cspr	**0.55**	**0.556**			**-0.291**		**0.572**
Csum	**0.605**	**0.759**	0.186		**-0.467**	**0.433**	**0.428**
Caut	**0.628**	**0.612**	*0.272*			0.183	**0.618**
Cyr	**0.614**	**0.525**	*0.264*	**0.324**	-0.191	**0.415**	**0.511**
Wwin			-0.172		**0.612**	**0.591**	-0.205
Wspr					**0.467**	0.203	
Wsum							
Waut			-0.18	-0.262	**0.296**		
Wyr					**0.445**		
NAOwin					**0.712**	**0.732**	
NAOspr					**0.474**	**0.375**	
NAOsum				-0.186			
NAOaut					**0.297**		
NAOyy					0.217		

Table 2

	Total rainfall	Rain days	Days >= 15	10-day totals
C winter	**0.417**	*0.275*	*0.231*	
C spring	**0.562**	**0.504**	**0.297**	*0.231*
C summer	**0.580**	**0.511**	**0.393**	0.175
C autumn	**0.479**	**0.444**	**0.334**	0.206
C year	**0.415**	0.224	**0.335**	0.189
W winter	*0.282*	**0.467**		
W spring	0.197	*0.276*		
W summer				
W autumn	**0.366**	**0.409**	***0.274***	0.199
W year	0.175	0.195		
NAO winter	**0.473**	**0.592**		
NAO spring	**0.288**	**0.381**		
NAO summer				
NAO autumn	**0.435**	**0.499**	**0.326**	*0.233*
NAO year	*0.281*	**0.426**		

Table 3

	A	C	N	E	S	W	NW
Exe	1.1%	56.9%	3.3%	4.7%	12.5%	20.0%	1.6%
Thames	13.6%	34.7%	6.0%	7.2%	13.0%	17.3%	8.1%
Tees	0.0%	50.2%	2.2%	3.3%	14.5%	25.7%	4.1%
Tay (day)	1.8%	34.4%	0.0%	0.5%	17.1%	40.3%	5.9%
Tay (day-1)	5.9%	15.3%	0.0%	1.4%	35.1%	41.4%	0.9%

Table 4